LRC 64-442

25 P

FACILITY FORM 602

N64-29569 (ACCESSION NUMBER)	(THRU)
25 (PAGES)	1 (CODE)
CR-58360 (NASA CR OR TMX OR AD NUMBER)	09 (CATEGORY)

OTS PRICE

XEROX $ 2.60 ph

MICROFILM $

JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA

M

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CONTRACT NO. NAS 7-100

Technical Memorandum No. 33-92

ELASTOMERIC PNEUMATIC LOGIC ELEMENTS

F. F. Batsch
J. H. Laub

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
August 1, 1962

CONTENTS

I. Introduction 1

II. Speed of Response 2

III. Operation and Logic 4

References 10

FIGURES

1a. Experimental arrangement for determining response time 11

1b-d. Typical oscillograms showing speed of response 11

2a. Schematic construction of basic element 12

2b. Symbol for basic element 12

3a. Dual AND element 13

3b. Pneumatic circuit, AND 13

4a. Exclusive OR element 14

4b. Pneumatic circuit, OR 14

5a. Bistable element 15

5b. Pneumatic circuit, bistable element 15

6a. Half-adder 16

6b. Pneumatic circuit, half-adder 16

7a. Pushbutton valve 17

7b. Pneumatic circuit, valve 17

8. NOT element 18

9. NOT-NOT element 18

10. NAND element 19

11. INHIBITOR element 19

FIGURES (Cont'd)

12. INCLUSIVE OR element 20

13. MULTI-INPUT AND element 20

14. NOR element 21

15. NAND element 21

ABSTRACT

29569

Pneumatic logic elements offer certain advantages over their electronic counterparts for operation of computers at relatively low speeds and under difficult environmental conditions. A study of elastic diaphragms and orifices, molded in various configurations from elastomers and applied as switching elements in a pneumatic array, is described. Power loss and cost of manufacture are low and response times adequate for operation at relatively low speed. Elastic diaphragms lend themselves readily to modular design.

Author

I. INTRODUCTION

Considerable interest has recently developed in pneumatic logic elements and circuitry for computer and controller applications. Pneumatic logic components and arrays are attractive for a number of reasons. They are relatively insensitive to extremes of temperature and to nuclear radiation and are not subject to electromagnetic "jamming." Pneumatic controls can be operated directly from pneumatic logic arrangements without the interposition of electronic circuitry. Manufacturing costs promise to be low owing to component simplicity and the use of inexpensive construction materials. Furthermore, power consumption and waste heat can be minimized.

II. SPEED OF RESPONSE

Applications of these elements, however, are confined to relatively slow operations since pneumatic pulses propagate at a much lower speed than electromagnetic waves. An estimate of the upper frequency limit of a pneumatic logic circuit can be obtained in the following manner. The maximum speed of propagation of a pressure wave in a gas is the sonic velocity c which, for air at 20°C and atmospheric pressure, is 1129 fps. It increases with temperature but is practically independent of pressure within the range of interest to logic applications. With the above value of c, the propagation time of a pressure pulse between two points in the logic array, 1 in. apart, becomes

$$t = \frac{1}{1129 \times 12} = 7.4 \times 10^{-5} \text{ sec}$$

and

$$t = 7.4 \times 10^{-6} \text{ sec for a distance of 0.1 in.}$$

Propagation distances of practical pneumatic circuits lie within these dimensions, which imply a frequency limit of 10^4 to 10^5 cps, not counting the response time of the pneumatic logic elements proper, which, of course, has to be added and is discussed later.

Various techniques for pneumatic logic switching elements have been developed. The opening and closing of ports by small spheres (Ref. 1), spool-type valves (Ref. 2), metal membranes or bellows (Ref. 3), and deflection of gas jets (Ref. 4) are examples of principles described in the literature.

Elastic orifices at the Jet Propulsion Laboratory were originally developed as control orifices for gas bearings, in which application their pressure-dependent performance results in important advantages (Ref. 5). In their simplest form, elastic orifices consist of small, thin, circular discs of an elastomer with a central hole having, in the relaxed, unpressurized state, a diameter of a few mils. Under compression, the hole shrinks and may close completely. A description of the orifice-type element can be found in Ref. 6.

The power required to operate elastic orifices depends on the particular design chosen; in any case, it is low. The order of magnitude can be estimated in the following manner: Assume an orifice whose diameter in the "full open" condition is 3.5×10^{-3} in., operating at $\Delta P = 8$ psi. The air flow through the orifice is

$Q = 5 \times 10^{-2}$ in.^{3}/sec, and hence the power loss $W = \Delta P \times Q = 8 \times 5 \times 10^{-2} = 4 \times 10^{-1}$ lb in./sec = 0.045 watt. The temperature rise resulting from this loss should be negligible since the heat is dissipated very effectively by convection in the gas stream.

The speed of response of a diaphragm-type element was measured experimentally by recording input step functions and output response times oscillographically. Figure 1a shows the experimental arrangement. The controlled and the controlling pressures P_1 and P_2, respectively, are recorded by means of variable reluctance diaphragm-type pressure transducers T_1 and T_2, which have a response time of 1 msec. Figures 1b-d are typical oscillograms taken on an elastic orifice of the diaphragm type as shown on Fig. 1a. The diameter of the diaphragm was 3/8 in., and the diameter of the port hole 0.031 in. The response time for both opening (Fig. 1c) and closing (Fig. 1b), defined by the time required for a 63% pressure change, is 5 msec in this case. The response time depends on the ratio of P_1 and P_2; by varying this ratio, response times of as low as 1 msec could be observed. As an example, the closing of the port with P_1 = 5 psig and P_2 = 20 psig is recorded in Fig. 1d. It should be noted that the experimental orifices were considerably larger than expected for actual logic applications.

Subsequent consideration of the type of logic element wherein a hole is molded through the elastomer has shown that reliability and time response are inferior to the diaphragm type of element hereinafter discussed. It was noticed that at times the hole did not completely close, causing some small leakage. Furthermore, and more importantly, it can be seen that if the exit flow were to be used to operate a downstream unit, the pressure difference could diminish and actually approach zero as a limit. This would have the effect of increasing the response time exponentially. Therefore, further work on this type of element has been suspended in favor of the diaphragm type. A discussion of the diaphragm type of logic element follows.

III. OPERATION AND LOGIC

Essentially, diaphragm-type element operation is that of a pneumatic valve that permits a flow of gas only when an input pressure is absent. In this sense, and in terms of symbolic logic, the valve then may be considered a NOT element:

$$\bar{A} = S$$

where S is the output and A is the input. Conversely

$$A = S$$

A characteristic of this element is that it is so constructed that if the gas pressures on both sides of the diaphragm are equal, or nearly so, there will be no output, regardless of the value of the pressures. It is this feature that permits the use of equal pressures for both input and output, thereby eliminating the necessity of boosting the pressure in circuitry calling for the output of one element to be the input of another.

Generally, there will be two pressure sources for a single logic element: a triggering, or input, pressure surge and a constant supply pressure (but not necessarily constant flow). Figure 2a is a schematic representation of the construction of the element under discussion; Fig. 2b is the symbolic representation used. The value of the minimum pressure necessary to lift the diaphragm is a function of the area, Young's modulus, Poisson's ratio of the elastomer, and the preload, or threshold, pressure. Of these parameters, the area and the threshold are the most easily variable. Therefore, an element may be designed to operate on any given minimum positive pressure. For example: if it is desired to operate the element at a pressure of 1 psig, such as may be obtained in a closed cycle system, then either the area or the threshold may be adjusted so that

$$P > \frac{W_p}{A}$$

where P is the given pressure, W_p is the threshold value in pounds, and A is the effective area of the diaphragm in in.^{2}. If the threshold is 0.1 lb, then the diameter of the diaphragm will be greater than 0.357 in. If it is desired to miniaturize the pneumatic element, the threshold must be as small as practicable and the pressure correspondingly increased.

The value of the threshold is determined by the compression of the diaphragm boss on the bottom of the socket. This value may be approximated from the formula

$$W_p = \frac{(L_{boss} - L_{socket})\, 2\pi E\, m^2\, t^3}{3(m^2 - 1)\left[\frac{1}{2}\,(r^2 - r_0^2) - \left(r_0^2 \ln \frac{r}{r_0}\right)\right]}$$

where W_p is the threshold in lb, E is the Young's modulus, m is the reciprocal of Poisson's ratio, r_0 is the radius of the boss, and $(L_{boss} - L_{socket})$ is the amount the diaphragm is deflected.

For use then in digital logic circuits, it is necessary only to apply a pressure greater than the minimum for satisfactory operation. The maximum pressure will be a function of the strength of the case in which the diaphragm is enclosed.

Another design factor that should be considered is the proper venting of the pressures that accumulate in the body or non-output portion of the circuit. Referring to Fig. 2, it will be seen that if a trigger pressure enters the upper chamber, it must be relieved after it has performed its function of shutting off the flow in the lower chamber in order to be receptive to the next pulse. This venting is accomplished by drilling a small hole in the case. The size of the vent hole is important inasmuch as too large a hole will reduce the pressure in the chamber to a value below the minimum, causing a false signal at the output, whereas too small a vent opening will slow down the speed of operation. A method of determining the proper size is given in an appendix.

Several laboratory models have been made and are being studied as digital logic operators. Figure 3a is a photograph of a dual AND element, i.e., two AND elements operating from a single supply source P_s; A and B are the input signals and C is the output. In logic symbols

$$C = \overline{\bar{A} + \bar{B}} = AB$$

The circuit for a single AND is shown in Fig. 3b.

Figure 4a is a photograph of an EXCLUSIVE OR element. The circuitry is shown in Fig. 4b. This circuit does not require a supply pressure but is operated solely from the trigger pulses. The output, in terms of inputs A and B, can be written

$$A\bar{B} + B\bar{A}$$

Figure 5a is a photograph of a two-input bistable device; Fig. 5b is the schematic circuit. Referring to the latter figure, P_1 and P_2, the supply lines, are shown separately, although in practice they may be manifolded and connected to a common source; A and B are the triggering pulses, and U and D are the outputs. A momentary pulse at A will give a continuous signal at U (supplied by P_2), while a pulse at B will change the flow output to D (supplied by P_1). This unit, by virtue of the continuous pressure (stable output) at either U or D, can be used as a non-destructive memory element.

Figure 6a is a photograph of a half adder; Fig. 6b shows the circuitry. The inputs are A and B and the outputs are S (sum) and C (carry). The Boolean equations for this particular circuit are:

$$S = A\bar{B} + B\bar{A}$$

$$C = A\bar{S}$$

The circuit would work equally well if it were redesigned so that

$$C = B\bar{S}$$

Figure 7 shows a device which has a manually operated pushbutton as an input and a pneumatic pulse as an output, the duration of the pulse being equal to the time the pushbutton is held down. This unit clearly demonstrates the action of a pair of elements connected in series. The subsequent figures indicate schematically a few possible logic elements. None of these have been constructed, but they contain principles already proven in the units previously described.

Figure 8 is in reality the basic element: an INVERTER or NOT

$$A = \bar{A}$$

$$\bar{A} = A$$

Figure 9 is the all-pneumatic equivalent of Fig. 7

$$A = A$$

$$\bar{A} = \bar{A}$$

Figure 10 is a NAND element

$$\bar{A} \text{ and } \bar{B} = AB$$

$$A \text{ and } B = \bar{A}\,\bar{B}$$

Figure 11 is an INHIBITOR

$$B \text{ unless } A$$

Figure 12 is an INCLUSIVE OR

$$A + B + AB$$

Figure 13 illustrates the type of circuitry for a multi-input AND

$$S = \overline{\bar{A} + \bar{B} + \bar{C} \cdots \bar{N}} = ABC \cdots N$$

Figure 14 is a NOR element

$$D = \overline{A + B + C} = \bar{A}\,\bar{B}\,\bar{C}$$

Figure 15 is a NAND element, which is the same as NOR except that the physical representation of "zero" and "one" are interchanged

$$D = \overline{AB} = \bar{A} + \bar{B}$$

Qualitative tests are now being conducted to determine the high and low-temperature limits of operation on the small half-adder. For this test, the body will be made of aluminum and the diaphragm of Silastic 501. It is also intended to expose the silicone rubber to various energy levels of gamma radiation to determine the amount of degradation necessary to make the element inoperative.

APPENDIX. Determination of Restrictor Size in a Pneumatic Element

Given the geometry and operating pressure, the problem is to find the optimum-size vent. It is obvious that the greater the flow from the pressurized chamber, the sooner the pressure will decrease sufficiently to allow the application of another positive signal. The maximum flow rate may be determined very simply by putting a flowmeter in series with the gas source and throttling the output until a value is reached above which the element will not function properly.

If the pressure ratio, that is,

$$\frac{P_1}{P_s} \leq \left(\frac{2}{k+1}\right)^{k/k-1}$$

the flow is sonic, where P_1 is the ambient pressure, P_s is the supply pressure, and k is the ratio of specific heats C_p/C_v. If

$$\frac{P_1}{P_s} > \left(\frac{2}{k+1}\right)^{k/k-1}$$

the flow is subsonic.

The equation for sonic flow through an orifice is

$$A = \frac{W}{\left(\frac{2}{k+1}\right)^{k+1/2(k-1)} \sqrt{\frac{kg}{RT}}\, P_s C_D}$$

and for subsonic flow:

$$A = \frac{W}{\left[\left(\frac{\left(\frac{P_s}{P_1}\right)^{k-1/k} - 1}{\left(\frac{P_s}{P_1}\right)^{k+1/k}}\right)\frac{2k}{k-1}\,\frac{g}{RT}\right]^{1/2} P_s C_D}$$

where A is the cross-sectional area of the orifice in in.^{2}, W is the flow rate in lb/sec, g is the gravitational constant in in./sec^2, R is the gas constant, T is the temperature in °R, and C_d is the orifice coefficient.

REFERENCES

1. "Pneumatic Computer Suitable for Space," *Aviation Week*, June 5, 1961, p. 81.

2. Glaettli, H. H., "Hydraulic Logic," *Control Engineering*, May 1961, p. 83.

3. Berends, T. K., and A. A. Tal, "Pneumatic Switching Circuits," *Automation and Remote Control*, Vol. 20, November 1959, pp. 1446-56.

4. "Combine Fluid Relays to Increase Their Versatility," *Control Engineering*, Vol. 6, February 1959, pp. 72-78.

5. Laub, J. H., "Elastic Orifices for Gas Bearings," *Journal of Basic Engineering*, December 1960, pp. 980-982.

6. *Research Summary No. 36-12, Vol. 1*, Jet Propulsion Laboratory, Pasadena, January 1962, pp. 35-39.

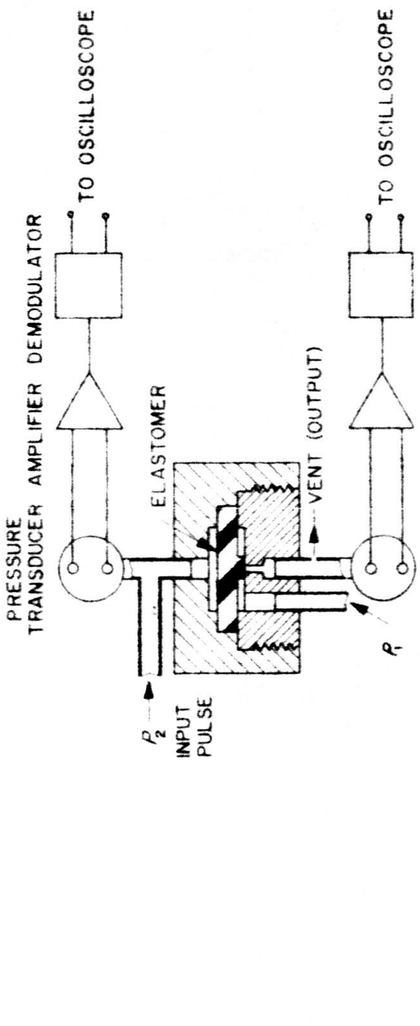
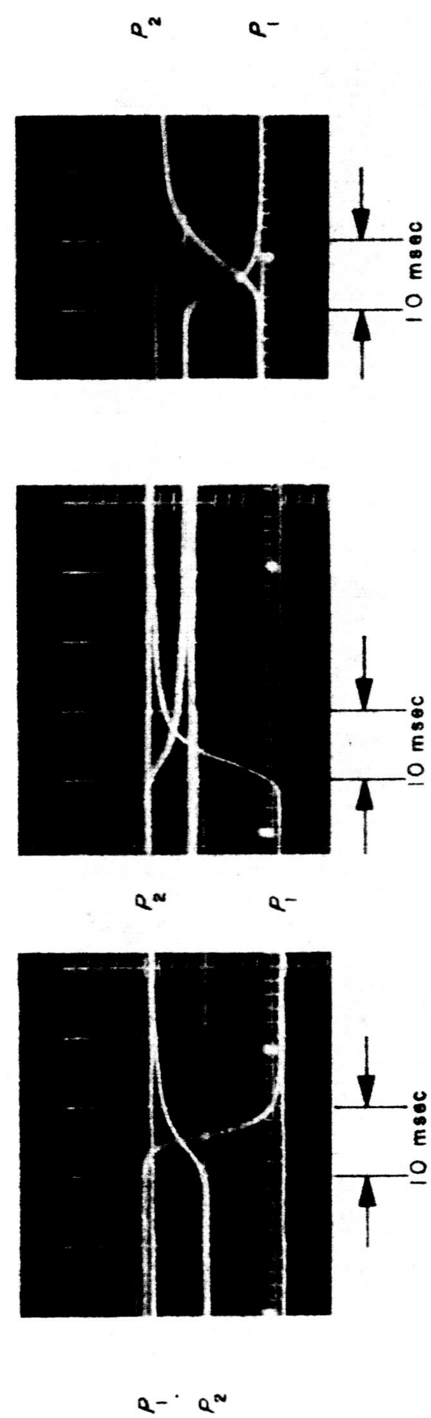


Fig. 1a. Experimental arrangement for determining response time



(b) CLOSING
$P_1 = 5; P_2 = 10$ psig

(c) OPENING
$P_1 = 5; P_2 = 10$ psig

(d) CLOSING
$P_1 = 5; P_2 = 20$ psig

Fig. 1b-d. Typical oscillograms showing speed of response

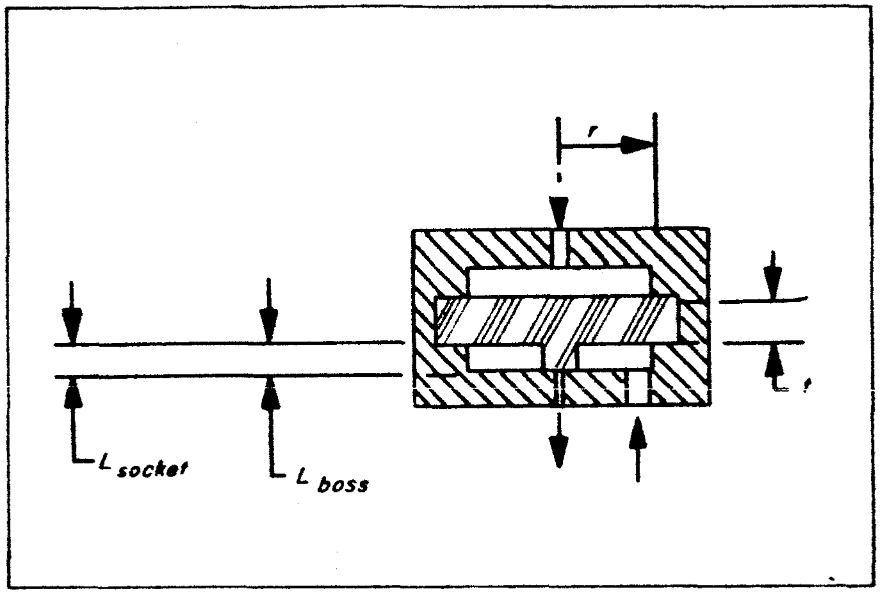


Fig. 2a. Schematic construction of basic element

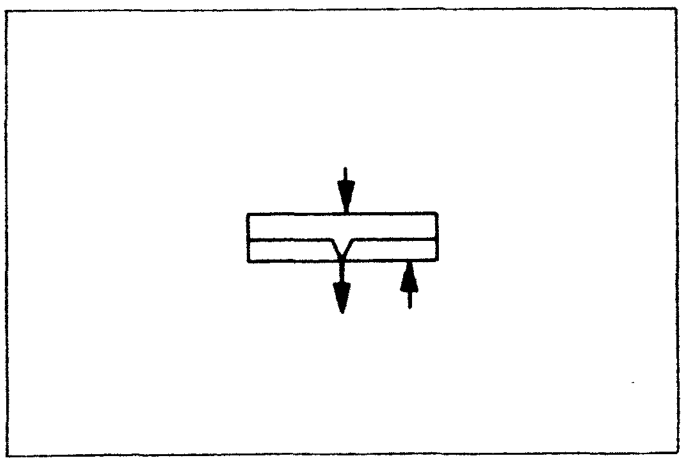


Fig. 2b. Symbol for basic element

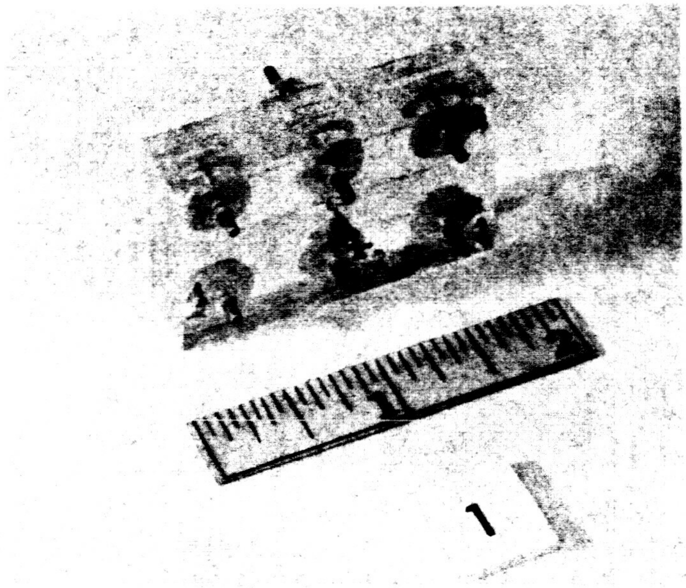


Fig. 3a. Dual AND element

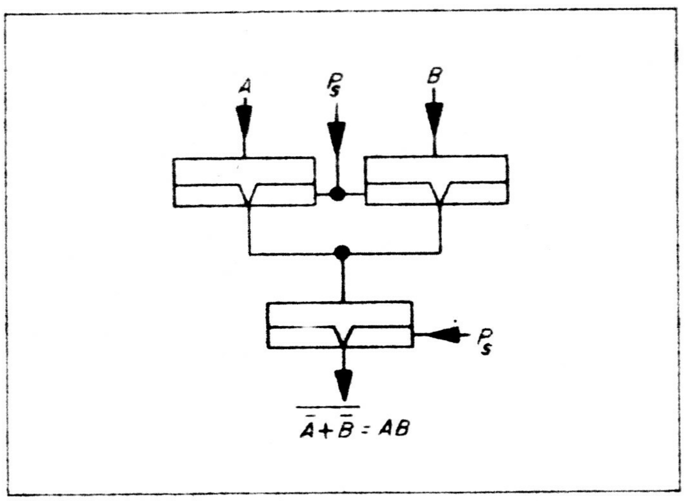


Fig. 3b. Pneumatic circuit, AND

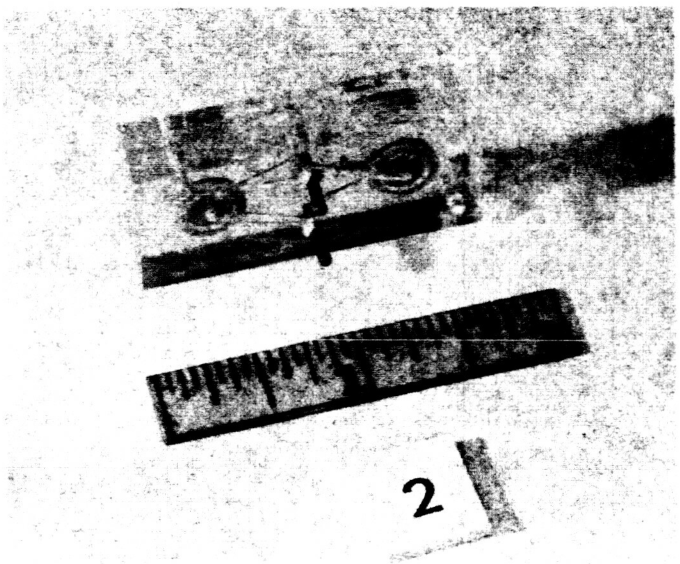


Fig. 4a. Exclusive OR element

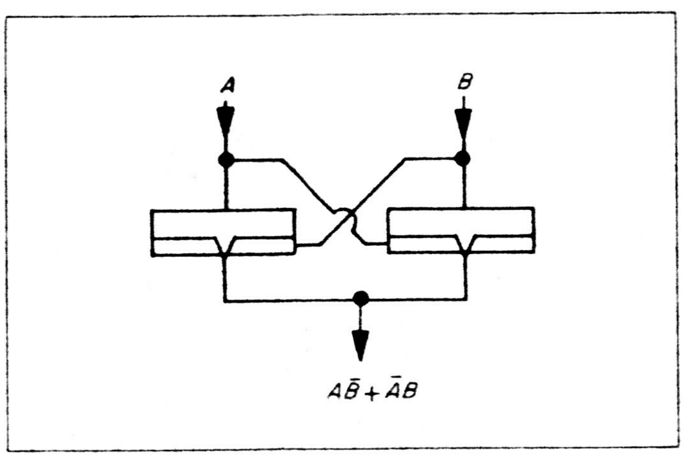


Fig. 4b. Pneumatic circuit, OR

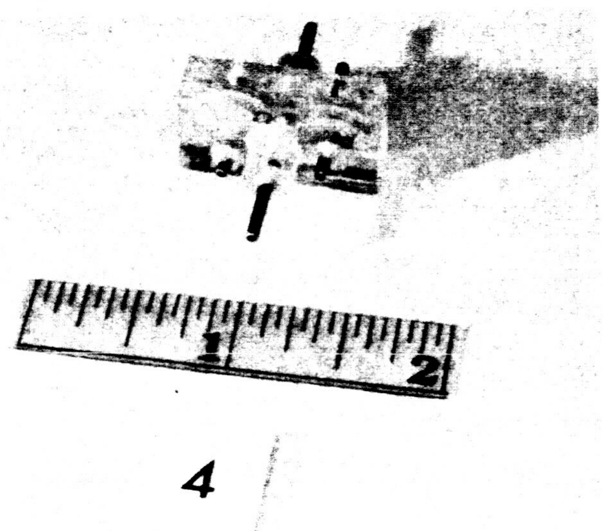


Fig. 5a. Bistable element

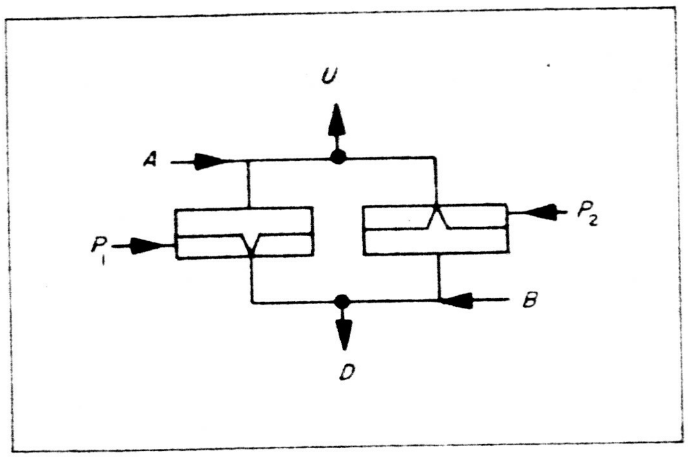


Fig. 5b. Pneumatic circuit, bistable element

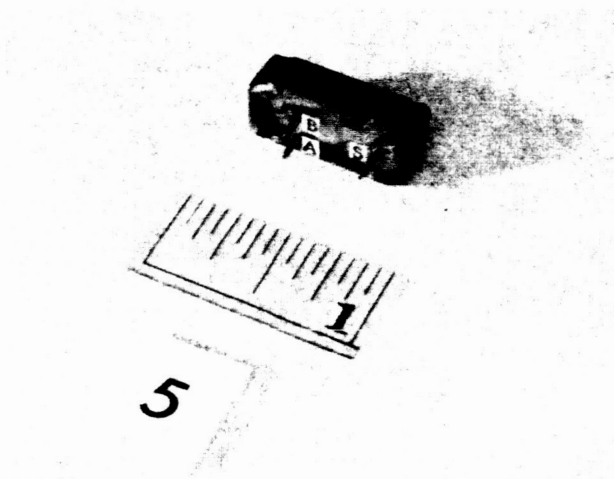


Fig. 6a. Half-adder

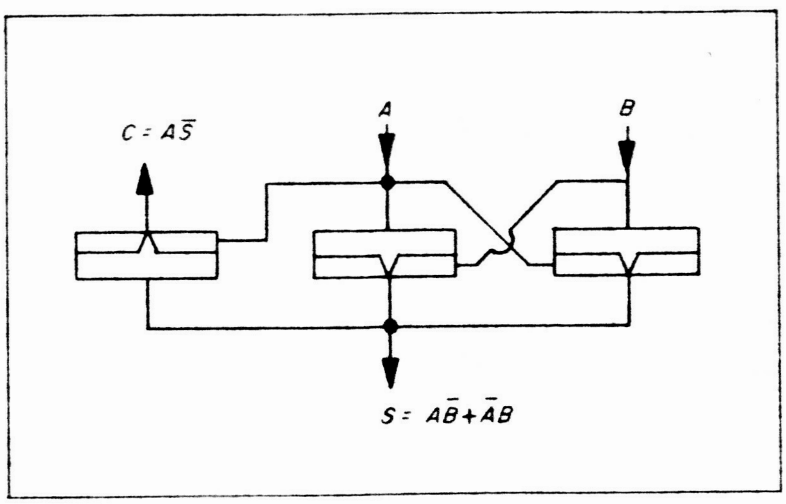


Fig. 6b. Pneumatic circuit, half-adder

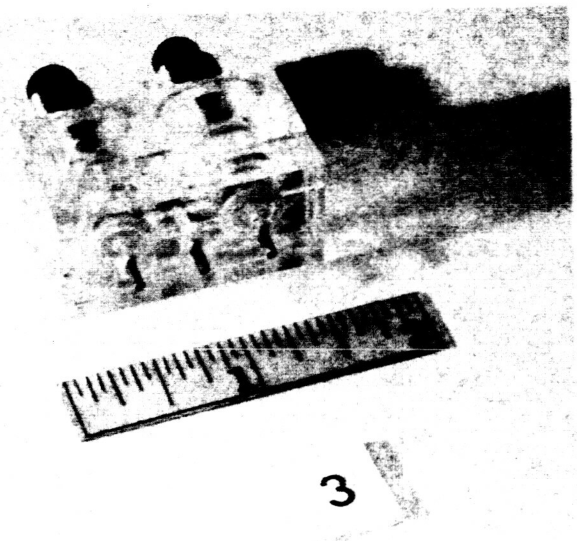


Fig. 7a. Pushbutton valve

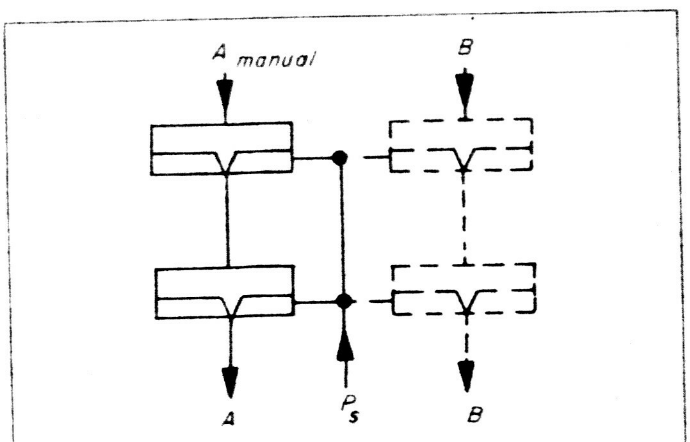


Fig. 7b. Pneumatic circuit, valve

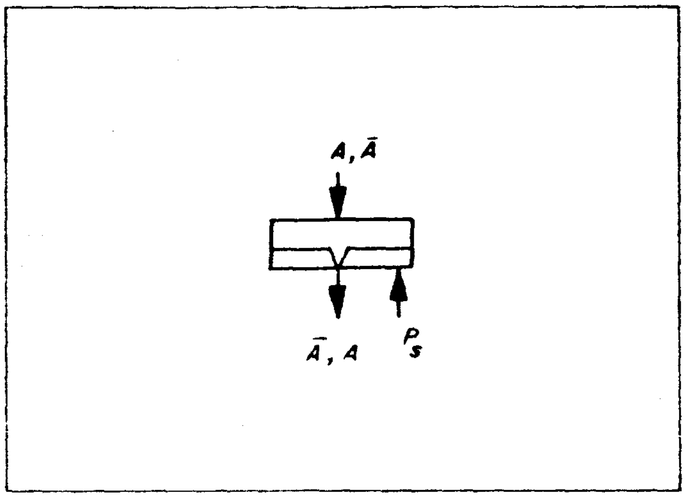


Fig. 8. NOT element

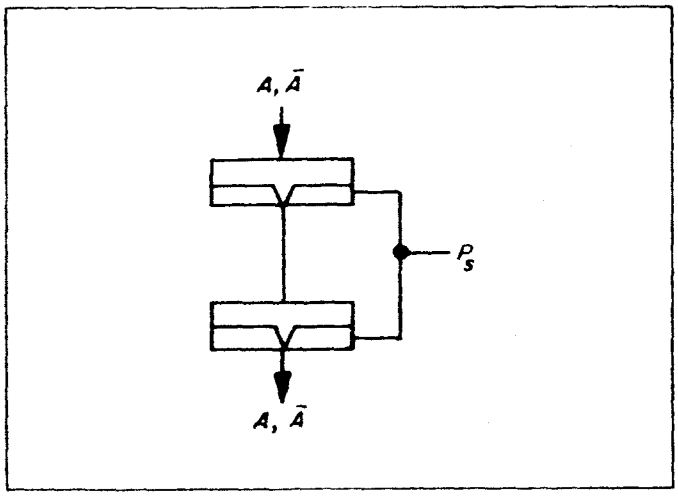


Fig. 9. NOT-NOT element

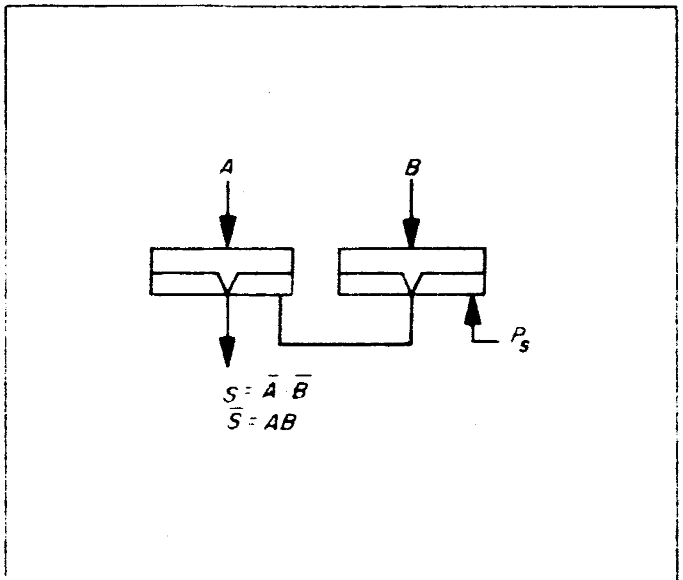


Fig. 10. NAND element

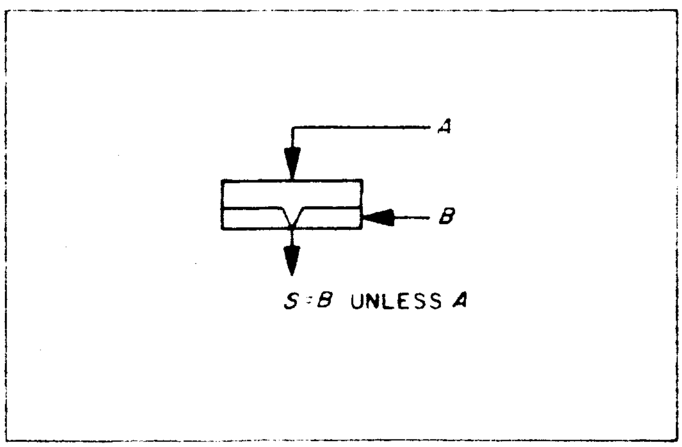


Fig. 11. INHIBITOR element

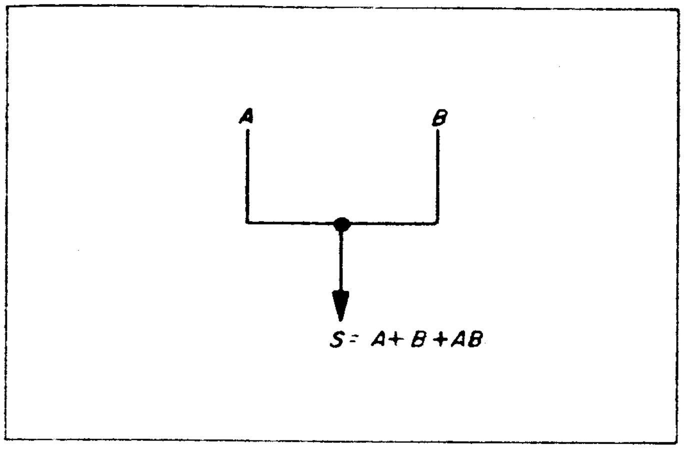


Fig. 12. INCLUSIVE OR element

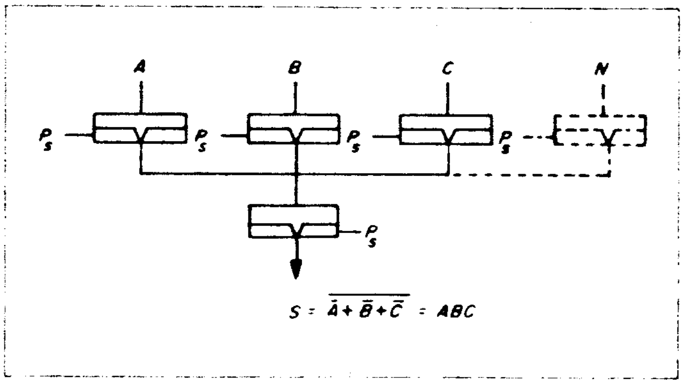


Fig. 13. MULTI-INPUT AND element

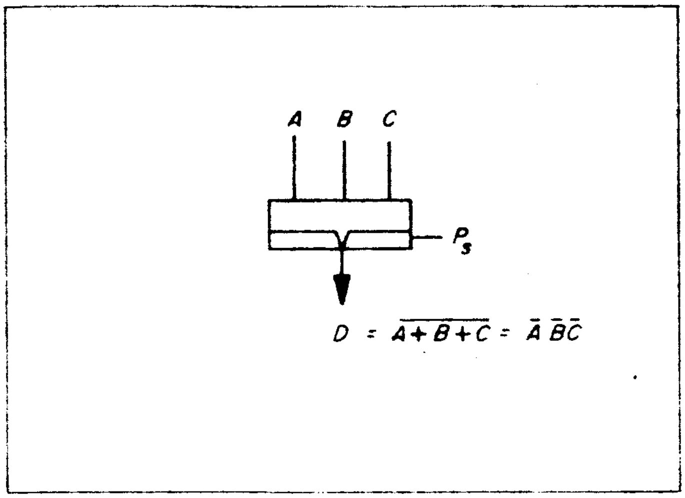


Fig. 14. NOR element

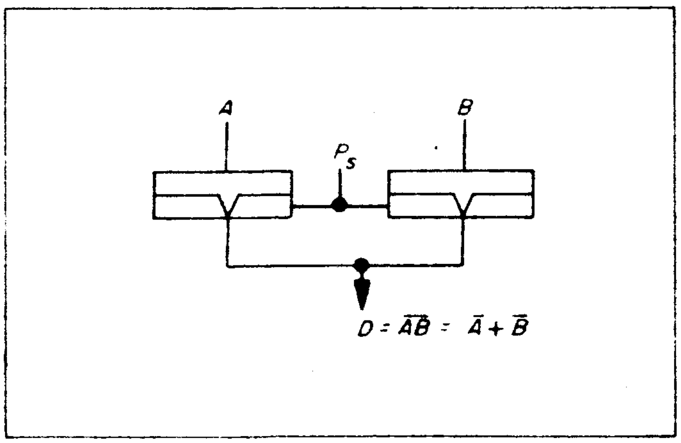


Fig. 15. NAND element